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J. W. Gibson and T. L. Wall
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Spatial distribution of fragments, I

by

J. W. Gibson, B.Sc., and T. L. Wall, B. Eng.

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SUMMARY

A long-term project has been planned to study in detail the spatial distribution of fragments from a warhead or casing of given specifications. The initial series have been completed and are discussed below. A formula is suggested as a first approximation for estimating the angle of projection of a fragment from its origin in the case wall and the limitations of the formula will form the basis for further experiment. The results of these small-scale trials are compared with the reported data from recent G.W. trials.

INTRODUCTORY THEORY

For may years a simple formula for estimating the direction of throw of fragments, derived from a theoretical treatment by Taylor (Ref.1), has been used with some confidence. Taylor considers the detonation of an explosive in an infinitely long heavy cylindrical case. He assumes a plane detonation wave without reflected waves (arising from expansion of the gases), that is, only the detonation wave and simple gas pressure affect the tube. The motion is discussed with reference to an observer moving with velocity U of the shock wave; the casing approaches the observer with a velocity U parallel to the axis and leaves him with a velocity U in a direction $(\pi - \theta)$ degrees. Direction is measured relative to the axis, the forward looking axial direction being 0 degrees. The angle θ is therefore the angle of coning (unrestrained by end effects) of the casing due to the expansion which follows the detonation front. Now bringing the observer to rest the resultant velocity is $2U \sin\frac{\theta}{2}$ in a direction $\frac{\pi}{2} - \frac{\theta}{2}$, this being the velocity of the fragment on projection in the direction given by

$$\sin\frac{\theta}{2} = \frac{V}{2U} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Applied to the standard shell design with nose or base initiation, the formula gives a reasonably good estimate of the average angle of throw, and when combined with a dispersion factor of say, ± 4 degrees, produces an acceptable fit to the experimental data from static fragmentation trials. In some instances, for example the thin-walled 3-in. U.P. shell, the shape of the casing permits close approximation to the premises required for Taylor's theory and the fit is then very good indeed. For other shells, an empirical modification of the formula, suggested by A.D.E., is found to be more suitable (Ref.2):-

$$\frac{\theta}{2} = 0.58 \sin^{-1}\frac{V}{2U} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The problem cannot be completely answered in terms of simple theory based on steady conditions of flow; in practice a casing has finite length and the type of end constraint is of major importance. The tube may be open-ended, or it may be closed by screwed-in plugs or by solid ends integral with the tube; in each case the end effect results in complexity of the detonation wave system and interferes with the 'coning' visualised in Taylor's infinite tube. Some interesting evidence was obtained from early experiments with the small "model bomb" casing developed at Buxton; this casing had a fragmenting length of 3.8 in., internal diameter 1-1/4 in. and screwed-in end plugs. Photographs showed that, on detonation (from one end), the casing became balloon-shaped prior to rupture; the central part was coned slightly, as suggested by theory, but at each end the tube was constrained to its original diameter. This bulging suggests that some of the casing at the initiator end will be projected slightly backwards with respect to the axial direction, and this is borne out by later experiments. With thick-walled casings, complete detonation may take place before the casing begins to rupture. In Fig. 1 three diagrams which illustrate the ballooning

of a casing during detonation are shown; 1a shows the original casing, and in 1b and 1c the detonation wave has moved to the positions as indicated along the length of the casing.

With the introduction of new designs, as in guided weapons, it became obvious that account must be taken of the position of the point of initiation, the spread of the detonation wave, and the end-effect. When the detonation wave strikes a uniformly thick wall of a casing normally the fragment will be projected normally; it would appear therefore that angles of projection of 0 and $\sin^{-1}\frac{V}{2U}$ degrees are the limiting cases corresponding with radial and longitudinal detonation waves, and that the inclusion of a simple trigonometrical function of the angle between the detonation wave and the surface of the casing should provide a means of gradation between the two limits.

Consider a casing in which the normal to the surface makes an angle ϕ with the axis (Fig. 2). Let the normal to the detonation wave at a point on the surface have direction α, all angles being measured from the nose. It now becomes very difficult to apply a treatment similar to Taylor's (Ref. 1) in view of the complexity of the shock wave system, but we shall attempt to extend his argument less rigorously. If the velocity of detonation is U, then the speed along the surface at the point of intersection of the detonation front and the surface of the casing is $U \sec\left(\frac{\pi}{2} + \alpha - \phi\right) = U^1$. If the casing behind the detonation wave is deflected through an angle θ, then, by applying similar reasoning to that used for long tubes, the resultant speed of the casing is $2U^1 \sin\frac{\theta}{2}$ in a direction $\phi - \frac{\theta}{2}$ where

$$\sin\frac{\theta}{2} = \frac{V}{2U}\cos\left(\frac{\pi}{2} + \alpha - \phi\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Thus the fragment is deflected from the normal to the surface (away from the detonation front) by an amount $\frac{\theta}{2}$ where $\frac{\pi}{2} + \alpha - \phi$ is the angle between the normal to the detonation wave and the surface of the casing. This angle may be estimated on the basis of Huygen's principle. With most solid fillings, where the velocity of detonation in the booster is almost the same as that in the main filling, the normal to the detonation front may be taken as the straight line to the nearest point on the detonator end surface; when the charge consists of an annulus of explosive, suitable adjustment must be made (Fig. 3).

A formula very similar to (3) which takes account of the shape of the detonation wave was suggested by Shapiro (Ref. 3). Shapiro regarded the phenomena of detonation from the viewpoint of a stationary observer and as Taylor points out the process is very complex since the expanding gases give kinetic energy to different parts of the case at different times. Shapiro suggested that, when the detonation wave reaches a point P on the surface, the case begins to move outwards with velocity $\frac{V}{2}$; in time δt the detonation travels along the casing to a point Q originally a distance $U \sec\left(\frac{\pi}{2} + \alpha - \phi\right)\delta t$ from P and thus the deflection from the normal to the surface is given by

$$\tan\theta' = \frac{V}{2U}\cos\left(\frac{\pi}{2} + \alpha - \phi\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

This argument is misleading as it suggests that θ' is a measure of the curvature of the casing following detonation, whereas in fact θ' is of the order of $\frac{\theta}{2}$, where θ is the angle through which the tangent to the surface

moves from its original position to the moment of projection.

It is emphasised, however, that formulas (3) and (4) give almost identical results when applied.

OBJECTS OF RESEARCH

It is apparent from the preceding section that there are many problems to be investigated in order to standardise the procedure for predicting the angular throw of fragments from a warhead of given size, shape and filling.

(i) The velocity of detonation is known for various explosive fillings but the effect of shape of the detonation wave should be investigated for cases where the wave does not assume a steady shape with respect to the wall, for example, in annular charges with symmetrical or asymmetrical initiation. Some aspects of this problem have been studied and a report is in preparation (Ref.4).

(ii) It is necessary to study the velocity of fragments originating from different points along the length of casing. The simple formulae suggested by Gurney (Ref.5) have been fitted to a wide range of data and provide good estimates of average speed, but it is uncertain to what extent the variation of speed from different portions of a shaped casing may be attributed solely to variation of E/C ratio. The degree and type of end restraint are believed to be important factors.

(iii) Formulas (3) and (4) describe the dispersion from a warhead which differs in two respects from the simple cylinder containing a plane detonation front. Account is taken of the point of initiation and of the fact that the casing may have a curved inner surface (in the axial plane). It may be necessary to study these factors separately. Moreover, independently of the shape of the inner wall, variation of the outer surface of the casing may alter the throw of fragments. End restraint must also affect the dispersion of neighbouring fragments apart from affecting fragment velocity.

(iv) The mechanical properties and dimensions of the casing, methods of controlling fragmentation (e.g. grooved charge, notched rings, pre-formed fragments) may affect dispersion either by altering velocity or by mechanical interaction of adjacent fragments. Additional factors encountered in warhead design, such as the effect of fairings around the casing, must also be considered.

EXPERIMENTAL METHOD

In order to obtain this information, a long-term research has been started. Most of the trials will be made with small casings fragmented in a strawboard layout giving almost 100 per cent. recovery. The strawboard packs of height 8 ft. and width 18 in. or 2 ft. are arranged tangentially along two semi-circular arcs at distances 5, 3 or 10 ft. from the casing (Fig.4). The casing is suspended in the centre of the layout with its axis vertical, 40 in. above packs laid on the ground. The strawboard packs are marked in horizontal zones each representing a 5-degree arc from the centre of the casing. Multi-velocity screens connected to an argon-lamp chronograph are arranged in the various zones (sometimes two or more vertically in one zone). The casing is engraved in order to assist correlation of both speed and direction of flight with the origin of the

fragments on the case. After detonation, the position, mass and depth of penetration of each fragment are recorded together with an associated velocity and an estimate of its original position in the casing. These raw data provide the means of examining the speed, dispersion and mass distribution of fragments from the sides of cased charges with different conditions of length, diameter, shape and material of casing; the effect of method of closure of the ends of the case, the position of the point of initiation, type of explosive and (for annular charges) the distribution of explosive within the casing can also be studied.

The first experiments in this programme have been analysed and the information which concerns fragment dispersion extracted. Two types of model casings have been used (Fig.5). The first was cylindrical, with a charge length of 4 in., internal diameter 1.25 in. and wall thickness 0.125 in.; the casing was filled with cast RDX/TNT 55/45 with inset C.E. booster, 0.55 in. diam., 0.45 in. long, initiated on the axis at one end; three casings were fired for natural fragmentation and three with grooved charges designed to produce 10 staggered rows of 13 fragments. The second type was a small barrel-shaped casing, again having a charge length of 4 in., wall thickness 0.125 in. and internal diameter varying on a circular arc from 1.25 to 2.00 in.; the filling was RDX/TNT 55/45 with similar end initiation. Two barrels were fired for natural fragmentation and a further two contained grooved charges having 10 staggered sections, each with 20 grooves. For both types of casing the grooved charges were produced by inserting fluted rubber liners into the casings prior to filling (Ref.6). All the casings were extended at each end to take screwed end pieces 1 in. thick.

The two model casings form a useful starting point for testing dispersion theory and the analysis of data has been co-ordinated with an examination of data from full scale static trials of some G.W. warheads. The data employed are as follows:-

(a) Model casing - cylinder
- Natural fragmentation - Series 1; 3 trials
- Control (grooved charge) - Series 2; 3 trials

(b) Model casing - barrel
- Natural fragmentation - Series 3; 2 trials
- Control (grooved charge) - Series 4; 2 trials

(c) G.W. Blue Sky (trials 4, 5, 9, 10, 11) (Ref.7)
- Control (notched rings) - 5 trials

(d) G.W. Red Shoes (trials 2, 3, 4) (Ref.7)
- Control (pre-formed fragments) - 3 trials

EXPERIMENTAL RESULTS

The data relating to spatial distribution from Series 1 to 4 are shown in the Appendix (Tables 1-14); much additional information concerning mass distributions, penetration into strawboard, secondary break-up, etc. will be discussed in a later report.

The zones in the strawboard layout are defined with respect to the centre of the casing but it is important that the angle of throw of a fragment should be measured from its point of projection from the wall. An error of 2 in. for example will result in an appreciable error in angle especially for fragments collected in the 3 ft.-radius packs. In the G.W. trials where fragments are collected at distances 30 and 45 ft. and casings are fragmented with the axis horizontal, the error is not so great. In order to make this correction, and in fact to enable a precise study of dispersion phenomena, it is desirable to have some means of identifying

fragments with respect to their point of projection. With controlled fragmentation this is comparatively simple, as the staggered rows of fragments resulting from the grooved charge are easily identified; with natural fragmentation great difficulty has been experienced in suitably engraving fragments without affecting the break-up of the casing, and it has been necessary to develop a procedure for estimating the point of projection from the dispersion data itself. The target sheets from the 3-ft. packs for a shot from each of Series 2 to 4 are shown in Fig.6; the regularity of the rows of holes resulting from the controlled casings is striking.

The dispersion data for a shot or series of similar shots may be represented by a weight histogram showing percentage weight of fragments collected against angular zone (as measured from the centre of the casing). Histograms for the four series are shown in Fig.7: from each we may draw a cumulative curve showing percentage weight of fragmented casing collected forward of angle θ, where θ varies between 0 and 180 degrees (Fig.8). From the dimensions of the casing, it is possible to calculate the variation of weight per unit length along its length, that is, if we imagine the casing (the portion between end plugs) to be divided into ten sections of equal width we may estimate the percentage weight of each. For the model bombs (Series 1, 2) these sections will each represent 10 per cent. of the casing; for the model barrels, (Series 3,4) the percentages are shown in Table 15.

TABLE 15 - Variation of weight along the length of a barrel-shaped casing

Section	1	2	3	4	5	6	7	8	9	10
Percentage weight	6.2	8.6	10.6	12.0	12.6	12.6	12.0	10.6	8.6	6.2

The point of projection of each section may be assumed to lie at the surface in the middle of the section in question. The dispersion angle (with respect to the centre of the casing) may now be estimated from the curves in Fig.8 by noting the centre point of the zones which contain successive increments of percentage weight given in Table 15 for barrel casings or equal increments of 10 per cent. for tubes. This dispersion angle must be corrected to give the true angle of throw from its point of projection and this involves simple trigonometrical calculation. This method of estimation has been adopted for Series 1 and 3 since it was often not possible to identify fragments with respect to point of projection, and values are given in Tables 16, 17.

TABLE 16 - Series 1; estimates of dispersion angles, degrees

Section	3-ft. collection		5-ft. collection		Average estimate
	Angle from centre	Estimated angle of projection	Angle from centre	Estimated angle of projection	
1	84.8	87.7	86.0	87.7	87.7
2	89.4	91.6	90.7	92.0	91.8
3	92.2	93.8	92.3	93.3	93.6
4	94.1	95.1	93.7	94.3	94.7
5	95.4	95.7	95.0	95.2	95.5
6	96.0	95.7	95.8	95.6	95.7
7	96.7	95.8	96.4	95.8	95.8
8	97.2	95.6	96.8	95.9	95.8
9	97.9	95.7	97.5	96.2	96.0
10	98.7	95.9	98.5	96.8	96.5

TABLE 17 - Series 3: estimates of dispersion angles, degrees

Section	3-ft. collection		5-ft. collection		Average estimate
	Angle from centre	Estimated angle of projection	Angle from centre	Estimated angle of projection	
1	70.0	72.6	73.8	75.4	74.0
2	77.0	79.1	78.8	80.1	80.6
3	81.2	82.8	82.2	83.1	83.0
4	86.0	87.0	86.3	86.9	87.0
5	91.3	91.6	90.8	91.0	91.3
6	96.5	96.2	95.4	95.2	95.7
7	100.6	99.7	99.8	99.2	99.5
8	106.5	105.0	104.1	103.2	104.1
9	110.7	108.7	108.3	107.1	107.9
10	114.0	111.6	112.4	110.9	111.3

With the controlled casings of Series 2 and 4, the dispersion angles may be estimated by a direct method and these "observed" angles may be compared with those estimated by the method of extrapolation outlined above; thus for Series 2 and 4 we may obtain dispersion angles in two ways and the comparisons are shown in Tables 18, 19.

TABLE 18 - Series 2; dispersion angles (degrees)

Section	Estimated angle	Observed angle
1	87.2	87.6
2	90.4	91.1
3	92.2	93.2
4	93.7	94.0
5	94.5	95.1
6	95.1	95.3
7	95.4	95.2
8	95.5	95.7
9	95.8	96.1
10	96.3	95.1

TABLE 19 - Series 4; dispersion angles (degrees)

Section	Estimated angle	Observed angle
1	72.5	72.6
2	77.1	79.4
3	81.1	82.5
4	85.8	87.4
5	91.2	93.9
6	96.7	97.5
7	102.1	101.2
8	106.9	106.1
9	110.0	110.0
10	114.0	113.4

It is emphasised that identification of fragments with respect to their points of projection is to be preferred whenever possible.

In order to test the validity of a formula such as (3), we must calculate the expected angles of throw predicted by the formula and compare these with observations. The expected dispersion angle is a function of velocity of projection V, velocity of detonation U, and the angles α and ϕ which may be calculated from the dimensions of the casing; an accurate estimate of velocity V is the most important requirement for the application of the formula, and we therefore need to know the velocity of each section of the case. These have been measured in the course of the experiments and are shown graphically in Figs. 9 and 10. Smooth curves have been fitted

to the points, and estimated velocities shown in Table 20 for series 2, 3 and 4; the recordings in Series 1 were not sufficiently numerous to permit accurate estimation of velocities from different points of a casing.

TABLE 20 - Velocities of fragments, ft./sec.

Section	Series 2	Series 3	Series 4
1	3840	4850	4270
2	4050	5020	4450
3	4220	5230	4630
4	4340	5480	4840
5	4410	5720	5050
6	4470	5950	5270
7	4520	6170	5450
8	4550	6350	5590
9	4530	6450	5700
10	4200	6450	5750

Using formula (3) expected dispersion angles have been calculated and are compared with the observed values (Table 21, Figs.11, 12, 13)

TABLE 21 - Dispersion angles, comparison of expected with observed, degrees

Section	Series 2		Series 3		Series 4	
	Expected	Observed	Expected	Observed	Expected	Observed
1	91.6	87.6	74.2	74.0	73.8	72.6
2	93.5	91.1	79.4	80.6	78.9	79.4
3	94.3	93.2	84.8	83.0	84.2	82.5
4	94.6	94.0	89.2	87.0	88.5	87.4
5	94.8	95.1	93.8	91.3	93.1	93.9
6	95.0	95.3	98.0	95.7	97.4	97.5
7	95.0	95.2	102.3	99.5	101.8	101.2
8	95.0	95.7	106.6	104.1	105.9	106.1
9	95.1	96.1	111.4	107.9	110.7	110.0
10	94.8	95.1	115.4	111.3	114.7	113.4

The data for series 1 to 4 are derived from the fragmentation of model casings; the results of some recent full-scale G.W. fragmentation trials have been analysed by a similar method and expected dispersion angles (calculated from equation (3)) compared with observed values. The angles together with smoothed velocities are given in Tables 22 and 23, and are shown graphically in Figs. 14 to 17. The warheads Red Shoes and Blue Sky have been described in detail (Ref.7); the former is made up of pre-formed 1/4-oz. fragments and for convenience the casing is divided into 20 sections. The Blue Sky casing comprises 33 notched rings, and is divided into 11 sections.

TABLE 22 - Red Shoes data, velocities (ft./sec.) and angles (degrees)

Section	Velocity	Dispersion angle	
		Expected	Observed
1	6750	67.2	64.5
2	7050	68.9	67.2
3	7220	70.8	69.5
4	7320	72.9	72.0
5	7380	75.2	74.6
6	7430	77.5	77.2
7	7440	80.1	80.0
8	7440	82.9	83.0
9	7440	85.9	85.8
10	7440	89.1	88.8
11	7440	90.9	91.6
12	7440	94.1	94.7
13	7440	97.1	97.5
14	7440	99.9	100.2
15	7440	102.5	103.3
16	7440	104.8	105.9
17	7400	107.3	108.4
18	7280	109.2	110.8
19	7050	111.1	112.8
20	6750	112.8	115.0

TABLE 23 - Blue Sky data, velocities (ft./sec.) and angles (degrees)

Section	Velocity	Dispersion angle	
		Expected	Observed
1	4700	81.0	75.7
2	4960	81.3	79.3
3	5070	82.0	81.7
4	5170	83.3	83.7
5	5270	85.9	85.8
6	5350	89.6	88.2
7	5410	92.4	90.4
8	5450	93.9	92.7
9	5450	95.0	95.1
10	5350	95.5	97.5
11	5150	95.5	100.0

CONCLUSIONS

(i) For natural fragmentation, the average speed is approximately that estimated from the Gurney formula, but there is a variation along the length of the casing which is not accounted for purely by variation of E/C ratio. With the cylindrical casing there is a reduction of speed towards the ends of the casing, which suggests that the type of end confinement is an important factor. There is also a suggestion that with end initiation the maximum speed of projection is not at the middle of the casing but at a short distance from the centre away from the initiator; these conclusions are borne out from the results with the small barrel-shaped casing. With grooved charge control the speeds are lower than from natural fragmentation and this may be due to the presence of the rubber liner and grooving of the charge with consequent reduction in H.E.

The Red Shoes data provide a good speed curve which is symmetrical (as the casing is symmetrical and initiation central) and again there is a falling-off of speed at the ends. It is difficult to make comparisons with speed formulae since with annular charges these formulae have not yet been firmly established. The Blue Sky records are also very comprehensive but again difficult to interpret owing to a large fuse cavity which runs centrally down on half of the charge.

(ii) On the basis of formula (3) or (4) the expected distributions agree very well with the observed. There is some departure at the ends of the casing which may represent a true deviation from the hypothesis; the estimates of fragment speed may, however, be unreliable in these regions, and again, the method of extrapolating the dispersion angles from the data is faulty near the ends of the casing (Tables 18, 19). For natural fragmentation it might be more exact to associate a dispersion factor with the theoretical formula; it is certainly true that fragment zones overlap to some extent, though with controlled casings, especially of the barrelled type the angular pattern is remarkably regular.

There is much information yet to be obtained from these trials, as for example, comparison of mass distributions, secondary break-up etc. The trials indicate further lines of research on angular distribution and suggest that it should be possible to solve the problem.

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APPENDIX

The Appendix contains the experimental data from Series 1 to 4 connected with spatial distribution of fragments. Tables 1 and 2 give summaries and descriptions of shots fired and collected results. Corresponding with each series there are four tables; the first gives raw data classified in three ways - into shots, collecting area and dispersion zones. Numbers and weights of fragments are shown; in the number column, the first number represents the total number of fragments collected and the second bracketed number represents the number of holes made in the strawboard packs. The second table in each series gives numbers and weights of fragments corrected to 360 degrees from that part of the casing which lies between the end plugs, that is, fragments from the threaded portions are excluded. The third and fourth tables show averages over collecting area and shots.

TABLE 1 - Summary of shots

Series	Number of shots	Dimensions of casing					Fragmentation	Collecting medium
		Total length, in.	Fragmented length, in.	Thickness of wall, in.	Shape	Internal diam., in.		
1	3	7.8	4.0	0.125	Cylinder	1.25	Natural	Strawboard
2	3	"	"	"	"	"	Controlled	"
3	2	6.5	4.0	0.125	Barrel	1.25 to 2.00	Natural	"
4	2	"	"	"	"	"	Controlled	"

TABLE 2 - Summary of results

Series	Shot	Weight of casing, gm.		Weight of explosive gm.	Fragments recovered					
					Total		3-ft. packs (170°)		5-ft. packs (190°)	
		Total	Fragmented part		Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.
1	A	511.5	262.7	121.8	432	220.4	191	104.3	241	116.1
	B	512.5	262.7	125.4	428	195.0	199	85.0	229	110.0
	C	515.5	262.7	122.0	417	214.1	188	97.9	229	116.2
2	A	431.5	276.6	116.5	129	232.2	59	113.4	70	118.8
	B	424.5	276.6	115.5	139	237.0	62	116.5	77	120.5
	C	427.5	276.6	116.0	119	201.4	45	86.2	74	115.2
3	A	584.5	443.5	252.5	650	354.9	311	161.3	339	193.6
	B	543.5	402.5	255.5	641	278.8	274	120.7	367	158.1
4	A	596.0	455.0	227.0	302	361.1	87	174.9	115	186.2
	B	578.5	437.5	225.0	226	355.0	99	157.0	127	198.0

TABLE 3 - Dispersion of fragments, Series 1 - Numbers and weights of fragments

Shot	1A				1B				1C			
Collecting arc	3-ft.		5-ft.		3-ft.		5-ft.		3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.
60			2 (2)	1.28			2 (2)	4.73				
60 - 65					2 (1)	0.45						
65 - 70							1 (1)	0.11				
70 - 75									2 (2)	0.35		
75 - 80			2 (2)	0.28	5 (5)	2.19	2 (2)	0.45	12 (11)	1.64	2 (2)	0.22
80 - 85	24 (22)	6.81	16 (16)	3.98	10 (9)	2.62	20 (17)	6.56	7 (7)	1.65	12 (11)	2.23
85 - 90	27 (22)	16.87	34 (28)	13.58	25 (17)	9.93	24 (16)	8.56	14 (12)	4.94	22 (20)	7.59
90 - 95	52 (32)	26.53	68 (52)	34.21	54 (35)	20.51	57 (44)	26.44	42 (34)	25.45	93 (63)	51.14
95 - 100	88 (48)	54.07	118 (70)	63.09	105 (46)	49.73	124 (63)	65.58	113 (66)	64.18	99 (67)	54.49
100 - 105			3 (3)	0.95			2 (2)	2.39			1 (1)	0.56
105 - 110	2 (1)	2.39	1 (1)	2.50	1 (1)	0.16	1 (1)	0.43	2 (2)	3.38	4 (3)	3.94
110 - 115	1 (1)	0.10	6 (3)	1.87	6 (6)	3.60	4 (4)	1.03				
115 - 120			2 (2)	1.42	5 (5)	4.70	3 (3)	2.52	5 (5)	3.34	1 (1)	0.58
120 - 125									5 (5)	7.14	5 (5)	5.47
125	10 (9)	20.60	1 (1)	0.53	5 (5)	9.42	1 (1)	6.69	10 (9)	39.94		
Sum	191 (124)	104.28	241 (171)	116.08	199 (112)	84.98	229 (144)	109.98	188 (130)	97.86	229 (164)	116.23
Dust		4.83		5.37		4.09		5.31		4.58		5.42
Total		109.11		121.45		89.07		115.29		102.44		121.65
Estimated weight of fragmented part, gm.	263				263				263			

TABLE 4 - Dispersion of fragments, Series 1 - Numbers and weights corrected to 360°

Shot	1A				1B				1C			
Collecting arc	3-ft.		5-ft.		3-ft.		5-ft.		3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.
75 - 80			4 (4)	0.24	15 (15)	2.58	5 (5)	0.41	31 (28)	1.67	4 (4)	0.19
80 - 85	58 (53)	6.53	35 (35)	3.42	30 (27)	3.08	46 (39)	5.96	18 (18)	1.68	26 (24)	1.92
85 - 90	65 (53)	16.18	74 (61)	11.68	74 (50)	11.69	55 (36)	7.78	36 (31)	5.04	48 (43)	6.53
90 - 95	125 (77)	25.44	148 (113)	29.42	159 (103)	24.14	130 (100)	24.03	108 (87)	26.15	201 (136)	43.98
95 - 100	212 (116)	51.85	256 (152)	54.26	310 (136)	58.51	283 (144)	59.61	290 (170)	65.46	214 (145)	46.86
100 - 105			7 (7)	0.88			5 (5)	2.21			2 (2)	0.52

TABLE 5 - Dispersion of fragments, Series 1
Averages over collecting arcs

Shot	1A		1B		1C	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.
75 - 80	2 (2)	0.12	10 (10)	1.50	18 (16)	0.93
80 - 85	47 (44)	4.96	38 (33)	4.52	22 (21)	1.80
85 - 90	70 (57)	13.93	65 (43)	9.74	42 (37)	5.79
90 - 95	137 (95)	27.43	145 (102)	24.09	155 (112)	35.07
95 - 100	234 (134)	53.06	197 (140)	59.06	252 (158)	56.16
100 - 105	4 (4)	0.50	3 (3)	1.09	1 (1)	0.25

TABLE 6 - Dispersion of fragments, Series 1
Averages over shots

Collecting arc	3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.
75 - 80	15 (14)	1.42	4 (4)	0.28
80 - 85	35 (33)	3.76	36 (33)	3.77
85 - 90	58 (45)	10.97	59 (47)	8.66
90 - 95	131 (89)	25.24	160 (116)	32.48
95 - 100	271 (131)	58.61	251 (147)	53.58
100 - 105			5 (5)	1.23

TABLE 7 - Dispersion of fragments, Series 2 - Numbers and weights of fragments

Shot	2A				2B				2C			
Collecting arc	3-ft.		5-ft.		3-ft.		5-ft.		3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.
60			1 (1)	0.21	1 (1)	0.15	1 (1)	1.12	1 (1)	2.18		
60 - 65			1 (1)	0.23	2 (2)	0.39			1 (1)			
65 - 70			1 (1)	0.18	3 (3)	0.50						
70 - .5					1 (1)	0.10	2 (2)	0.57				
75 - 80												
80 - 85	3 (3)	6.43	2 (2)	2.32					6 (5)	13.38	2 (2)	0.29
85 - 90	9 (9)	19.33	10 (9)	19.26	13 (12)	25.24	15 (12)	25.57	1 (1)	2.02	12 (12)	24.15
90 - 95	15 (15)	30.49	20 (20)	37.66	16 (15)	28.95	31 (29)	43.02	14 (14)	25.12	29 (26)	41.70
95 - 100	32 (29)	57.13	38 (35)	59.05	33 (31)	62.34	30 (29)	49.99	24 (24)	45.71	31 (30)	49.09
100 - 105			1 (1)	0.46			1 (1)	1.92				
105 - 110							4 (4)	1.04				
110 - 115							2 (2)	11.73				
115 - 120			1 (1)	0.10								
120 - 125									1 (1)	0.11		
125	1 (1)	.10			7 (7)	1.45			4 (4)	0.72		
Sum	59 (56)	113.38	70 (66)	118.75	62 (58)	116.53	77 (71)	120.50	45 (45)	86.23	74 (70)	115.23
Dust		5.88		6.12		4.67		4.83		3.00		4.00
Total		119.26		124.87		121.20		125.33		89.23		119.23
Estimated weight of fragment part, gm.	263				263				263			

TABLE 8 – Dispersion of fragments, Series 2 – Numbers and weights corrected to 360°

Shot	2A				2B				2C			
Collecting arc	3-ft.		5-ft.		3-ft.		5-ft.		3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.
75 – 80												
80 – 85	7 (7)	5.67	4 (4)	1.95					18 (18)	15.51	4 (4)	0.25
85 – 90	20 (20)	17.05	21 (19)	16.22	28 (26)	21.66	31 (25)	21.22	3 (3)	2.34	26 (26)	20.96
90 – 95	33 (33)	26.89	42 (42)	31.71	35 (33)	24.84	65 (68)	35.70	41 (41)	29.11	64 (57)	36.19
95 – 100	71 (64)	50.38	80 (74)	49.73	72 (67)	53.49	63 (61)	41.48	71 (71)	52.98	68 (66)	42.60
100 – 105			2 (2)	0.39			2 (2)	1.59				

TABLE 9 – Dispersion of fragments, Series 2
Averages over collecting arcs

Shot	2A		2B		2C	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.
75 – 80						
80 – 85	5 (6)	3.81			11 (11)	7.88
85 – 90	21 (20)	16.64	30 (26)	21.44	15 (15)	11.65
90 – 95	38 (38)	29.30	50 (47)	30.27	53 (49)	32.65
95 – 100	76 (69)	50.06	68 (64)	47.49	70 (69)	47.79
100 – 105	1 (1)	0.20	1 (1)	0.79		

TABLE 10 – Dispersion of fragments, Series 2
Averages over shots

Collecting arc	3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.
75 – 80				
80 – 85	10 (10)	7.06	3 (3)	0.73
85 – 90	17 (16)	13.68	29 (23)	19.47
90 – 95	36 (36)	26.95	57 (53)	34.53
95 – 100	71 (67)	52.28	70 (67)	44.60
100 – 105			1 (1)	0.66

TABLE 11 - Dispersion of fragments, Series 3 - Numbers and weights of fragments

Shot	3A				3B			
Collecting arc	3-ft.		5-ft.		3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.
60			5 (5)	1.85	6 (6)	1.37	20 (20)	4.43
60 - 65	6 (6)	1.32	5 (5)	1.27	9 (9)	2.80	6 (6)	1.22
65 - 70	12 (12)	3.41	10 (10)	2.30	3 (3)	1.03	7 (6)	1.20
70 - 75	20 (18)	7.55	18 (16)	5.19	13 (11)	4.89	6 (5)	2.48
75 - 80	15 (14)	5.41	17 (16)	6.17	18 (18)	7.28	33 (25)	14.04
80 - 85	29 (21)	22.10	42 (34)	26.86	40 (26)	30.57	61 (42)	38.86
85 - 90	24 (17)	15.87	34 (28)	32.86	15 (13)	8.83	31 (27)	18.03
90 - 95	42 (29)	26.48	26 (22)	15.11	31 (25)	13.60	33 (26)	9.46
95 - 100	33 (27)	11.44	27 (24)	15.91	33 (25)	15.68	76 (56)	35.22
100 - 105	37 (28)	17.65	54 (40)	41.61	43 (32)	16.91	45 (38)	17.75
105 - 110	38 (27)	26.38	47 (26)	21.51	25 (18)	6.83	26 (21)	7.47
110 - 115	49 (36)	21.94	58 (35)	24.65	32 (22)	9.42	26 (21)	7.90
115 - 120	7 (6)	1.78	1 (1)	.14	12 (9)	2.86	17 (13)	4.46
120 - 125	7 (5)	2.23	3 (3)	.67	12 (11)	5.36	13 (12)	5.18
125	24 (24)	11.35			17 (17)	19.94	1 (1)	.13
Sum	311 (241)	161.33	339 (257)	193.58	274 (2[illegible]1)	120.70	367 (286)	158.09
Dust		16.36		19.64		21.21		26.79
Total		177.69		213.22		141.91		184.88
Estimated weight of fragmented part, gm.	412				371			

TABLE 12 - Dispersion of fragments, Series 3 - Numbers and weights corrected to 360°

Shot	3A				3B			
Collecting arc	3-ft.		5-ft.		3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.
60 - 65	14 (14)	0.82	10 (10)	0.66	24 (24)	2.32	12 (12)	0.77
65 - 70	28 (28)	2.11	19 (19)	1.19	8 (8)	0.85	14 (12)	0.76
70 - 75	46 (42)	4.68	35 (31)	2.68	34 (29)	4.05	12 (10)	1.57
75 - 80	35 (32)	3.35	33 (31)	3.19	47 (47)	6.03	66 (50)	8.88
80 - 85	67 (49)	13.70	81 (66)	13.88	105 (68)	25.33	122 (84)	24.58
85 - 90	56 (39)	9.84	66 (54)	16.98	39 (34)	7.32	62 (54)	14.04
90 - 95	97 (67)	16.41	50 (43)	7.81	81 (65)	11.27	66 (52)	5.98
95 - 100	76 (63)	7.09	53 (46)	8.22	86 (65)	12.99	152 (112)	22.28
100 - 105	86 (65)	10.94	104 (77)	21.50	112 (84)	14.01	90 (76)	11.23
105 - 110	88 (67)	16.35	91 (50)	11.11	65 (47)	5.66	52 (42)	4.72
110 - 115	114 (83)	13.60	112 (68)	12.73	84 (58)	7.80	52 (42)	5.00
115 - 120	16 (14)	1.10	2 (2)	0.07	32 (24)	2.37	34 (26)	2.82

TABLE 13 - Dispersion of fragments, Series 3
Averages over collecting arcs

Shot	3A		3B	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.
60 - 65	12 (12)	0.74	18 (18)	1.55
65 - 70	24 (24)	1.65	11 (10)	0.81
70 - 75	41 (37)	3.68	23 (20)	2.81
75 - 80	34 (32)	3.27	57 (49)	7.46
80 - 85	74 (58)	13.79	114 (76)	24.96
85 - 90	61 (47)	13.41	51 (44)	10.68
90 - 95	74 (55)	12.11	74 (64)	8.63
95 - 100	65 (55)	7.66	119 (89)	17.64
100 - 105	95 (71)	16.22	101 (80)	12.62
105 - 110	90 (58)	13.73	59 (45)	5.19
110 - 115	113 (76)	13.17	68 (50)	6.90
115 - 120	9 (8)	0.59	33 (25)	2.60

TABLE 14 - Dispersion of fragments, Series 3
Averages over shots

Collecting arc	3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.
60 - 65	19 (19)	1.57	11 (11)	0.72
65 - 70	18 (18)	1.48	17 (16)	0.98
70 - 75	40 (36)	4.37	24 (21)	2.13
75 - 80	41 (40)	4.69	50 (41)	6.04
80 - 85	86 (59)	19.52	102 (75)	19.23
85 - 90	43 (37)	8.58	64 (54)	15.51
90 - 95	89 (66)	13.84	58 (48)	6.90
95 - 100	81 (64)	10.04	102 (79)	15.25
100 - 105	99 (75)	12.48	97 (79)	16.37
105 - 110	77 (57)	11.01	72 (46)	7.92
110 - 115	99 (71)	10.70	82 (55)	8.87
115 - 120	24 (19)	1.72	18 (14)	0.08

TABLE 15 - Dispersion of fragments, Series 4 - Numbers and weights of fragments

Shot	4A				4B			
Collecting arc	3-ft.		5-ft.		3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.	Number	Wgt., gm.
60			1 (1)	.18	1 (1)	.14	3 (3)	2.27
60 - 65					2 (1)	2.11	1 (1)	.11
65 - 70	2 (2)	4.12	1 (1)	.30	5 (5)	9.26	2 (2)	3.60
70 - 75	6 (6)	12.35	11 (10)	18.93	5 (4)	7.51	7 (7)	12.61
75 - 80	9 (9)	19.26	12 (12)	21.42	10 (9)	14.18	9 (9)	17.38
80 - 85	9 (9)	20.46	9 (9)	19.86	15 (11)	18.80	10 (10)	21.85
85 - 90	9 (8)	19.60	9 (8)	18.67	10 (8)	17.24	11 (10)	22.95
90 - 95	11 (11)	20.26	12 (12)	24.04	6 (6)	9.74	8 (8)	13.13
95 - 100	8 (8)	17.56	13 (12)	21.20	10 (8)	16.47	20 (19)	25.57
100 - 105	7 (7)	15.53	11 (11)	19.36	9 (9)	18.12	18 (15)	20.50
105 - 110	10 (10)	20.27	14 (12)	21.62	13 (13)	21.44	12 (12)	21.06
110 - 115	10 (10)	17.18	21 (19)	28.67	14 (13)	21.12	22 (20)	30.73
115 - 120	6 (6)	8.35	2 (2)	2.15	2 (2)	3.16	8 (8)	8.60
120 - 125					8 (7)	1.91	5 (5)	1.19
125	18 (18)	5.89			23 (22)	16.65		
Sum	87 (86)	174.94	115 (108)	186.22	99 (88)	157.04	127 (120)	197.98
Dust		5.42		6.08		4.99		6.31
Total		180.36		192.30		162.03		204.29
Estimated weight of fragmented part, gm.	424				406			

TABLE 16 – Dispersion of fragments, Series 4 – Numbers and weights corrected to 360°

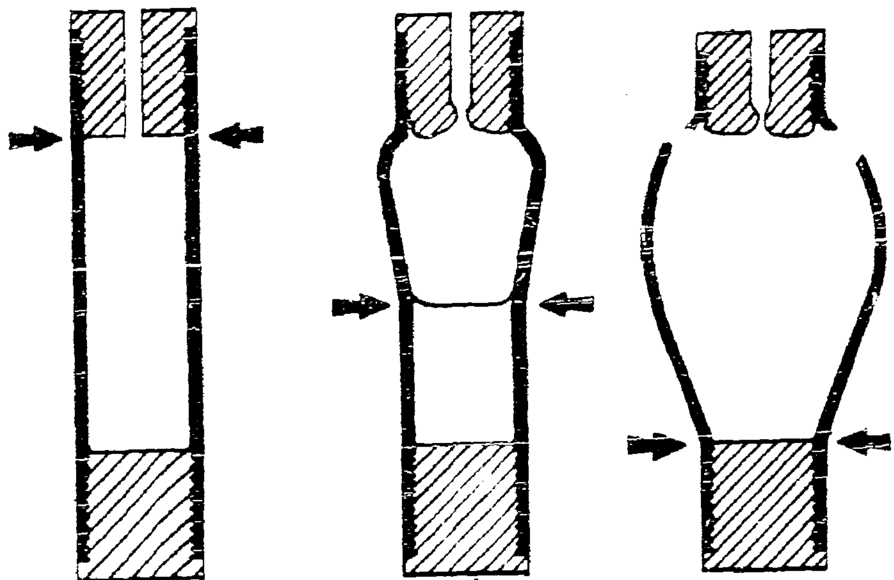
Shot	4A				4B			
Collecting arc	3-ft.		5-ft.		3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.	Number	Wgt., per cent.
65 – 70	5 (5)	2.35	2 (2)	0.15	13 (13)	5.90	4 (4)	1.82
70 – 75	14 (14)	7.06	23 (21)	9.91	13 (10)	4.78	14 (14)	6.37
75 – 80	21 (21)	11.01	25 (25)	9.41	25 (23)	9.03	18 (18)	8.78
80 – 85	21 (21)	11.69	19 (19)	10.39	38 (28)	11.97	20 (20)	11.04
85 – 90	21 (19)	11.20	19 (17)	9.76	25 (20)	10.98	22 (20)	11.59
90 – 95	26 (26)	11.58	25 (25)	12.58	15 (15)	6.20	16 (16)	6.63
95 – 100	19 (19)	10.04	27 (25)	11.09	25 (20)	10.49	40 (38)	12.92
100 – 105	16 (16)	8.88	23 (23)	10.12	23 (23)	11.54	36 (30)	10.35
105 – 110	24 (24)	11.59	29 (25)	10.45	33 (33)	13.65	24 (24)	10.64
110 – 115	24 (24)	9.82	44 (40)	15.00	35 (33)	13.45	44 (40)	15.52
115 – 120	14 (14)	4.77	4 (4)	1.14	5 (5)	2.01	16 (16)	4.34

TABLE 17 - Dispersion of fragments, Series 4
Averages over collecting area

Shot	4A		4B	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.
65 - 70	4 (4)	1.20	9 (9)	3.86
70 - 75	19 (18)	8.36	14 (12)	5.58
75 - 80	23 (23)	10.09	22 (21)	8.91
80 - 85	20 (20)	10.91	29 (24)	11.51
85 - 90	20 (18)	10.36	24 (20)	11.29
90 - 95	26 (26)	11.92	16 (16)	6.42
95 - 100	23 (22)	10.42	33 (29)	11.71
100 - 105	20 (20)	9.37	29 (29)	10.95
105 - 110	27 (25)	10.89	29 (29)	12.15
110 - 115	34 (32)	12.22	40 (37)	14.49
115 - 120	9 (9)	2.94	11 (11)	3.18

TABLE 18 - Dispersion of fragments, Series 4
Averages over shots

Collecting arc	3-ft.		5-ft.	
Zone of dispersion, degrees	Number	Wgt., per cent.	Number	Wgt., per cent.
65 - 70	9 (9)	4.13	3 (3)	0.99
70 - 75	14 (12)	5.92	19 (18)	8.14
75 - 80	23 (22)	10.02	22 (22)	9.10
80 - 85	30 (25)	11.83	20 (20)	10.72
85 - 90	23 (20)	11.09	21 (19)	10.63
90 - 95	21 (21)	8.89	21 (21)	9.61
95 - 100	22 (20)	10.27	33 (32)	12.01
100 - 105	20 (20)	10.21	30 (27)	10.24
105 - 110	29 (29)	12.62	27 (25)	10.55
110 - 115	30 (29)	11.64	44 (40)	15.26
115 - 120	10 (10)	3.39	10 (10)	2.70



(a) (b) (c)

STAGES IN DETONATION OF CASED CHARGE
(ARROW DENOTES POSITION OF DETONATION WAVE)

FIG. 1

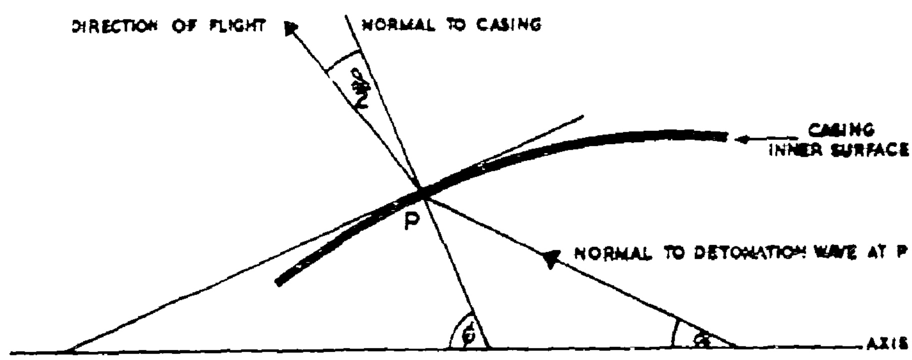


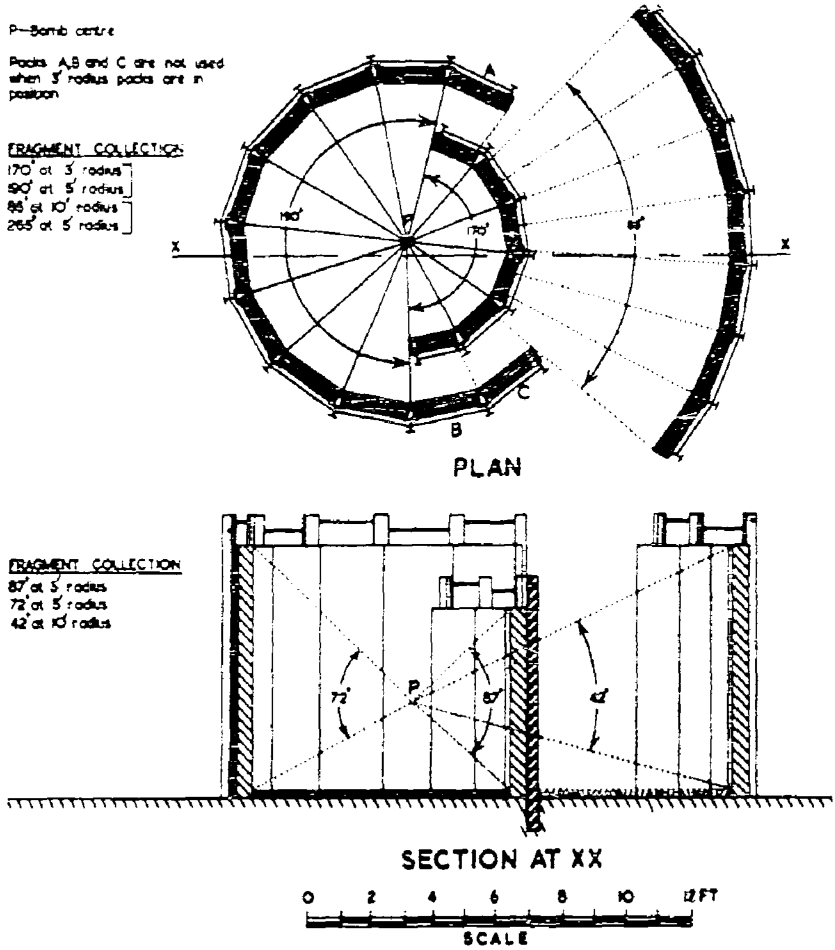
DIAGRAM SHOWING ANGLES
IN DISPERSION FORMULA

FIG. 2

(a) SOLID CHARGE (b) ANNULAR CHARGE

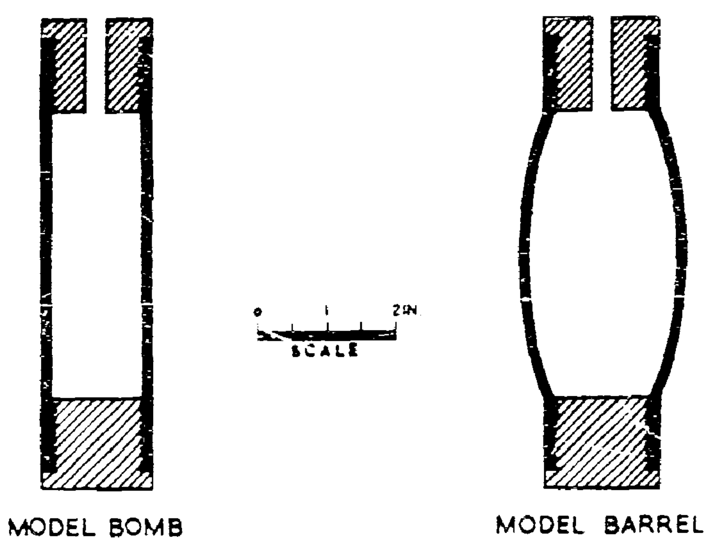
DIAGRAM SHOWING DIRECTIONS NORMAL TO
DETONATION WAVE

FIG. 3



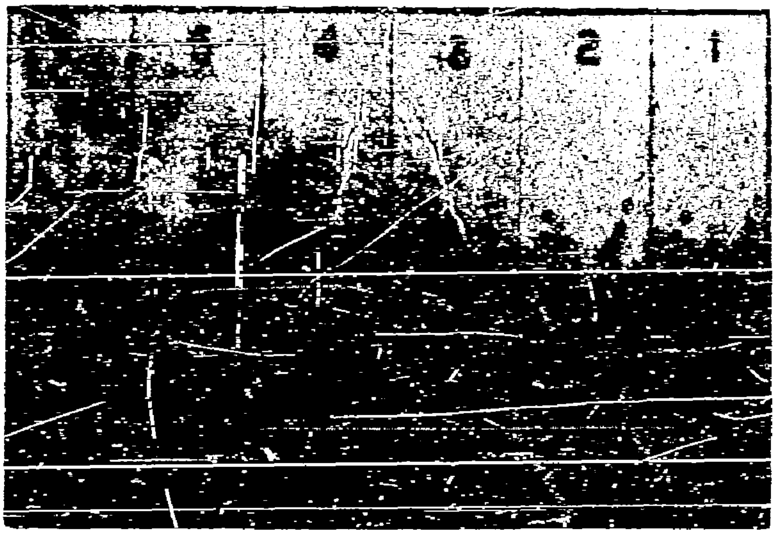
STRAWBOARD LAYOUT FOR STUDY OF FRAGMENT DISPERSION

FIG. 4

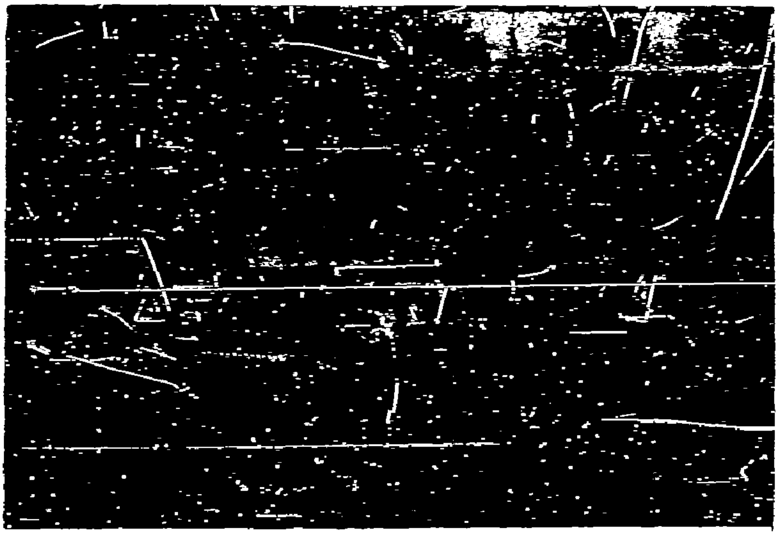


SECTIONS OF MODEL CASINGS

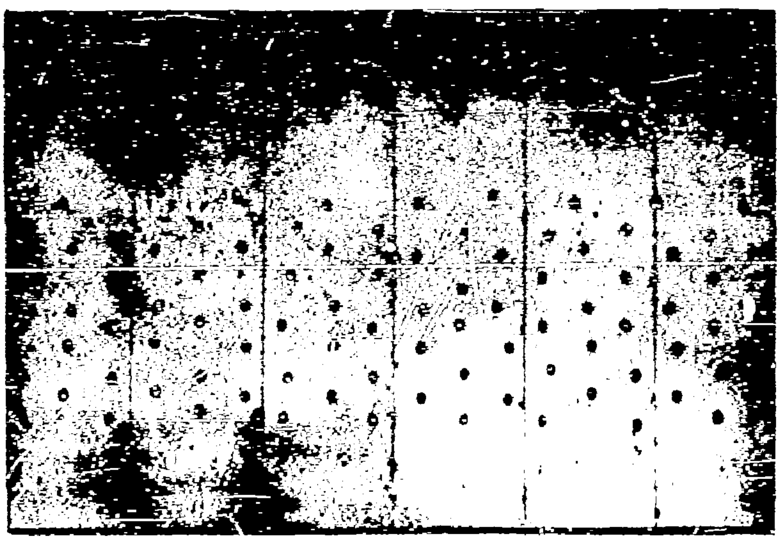
FIG. 5



SERIES.2 — MODEL BOMB, CONTROL



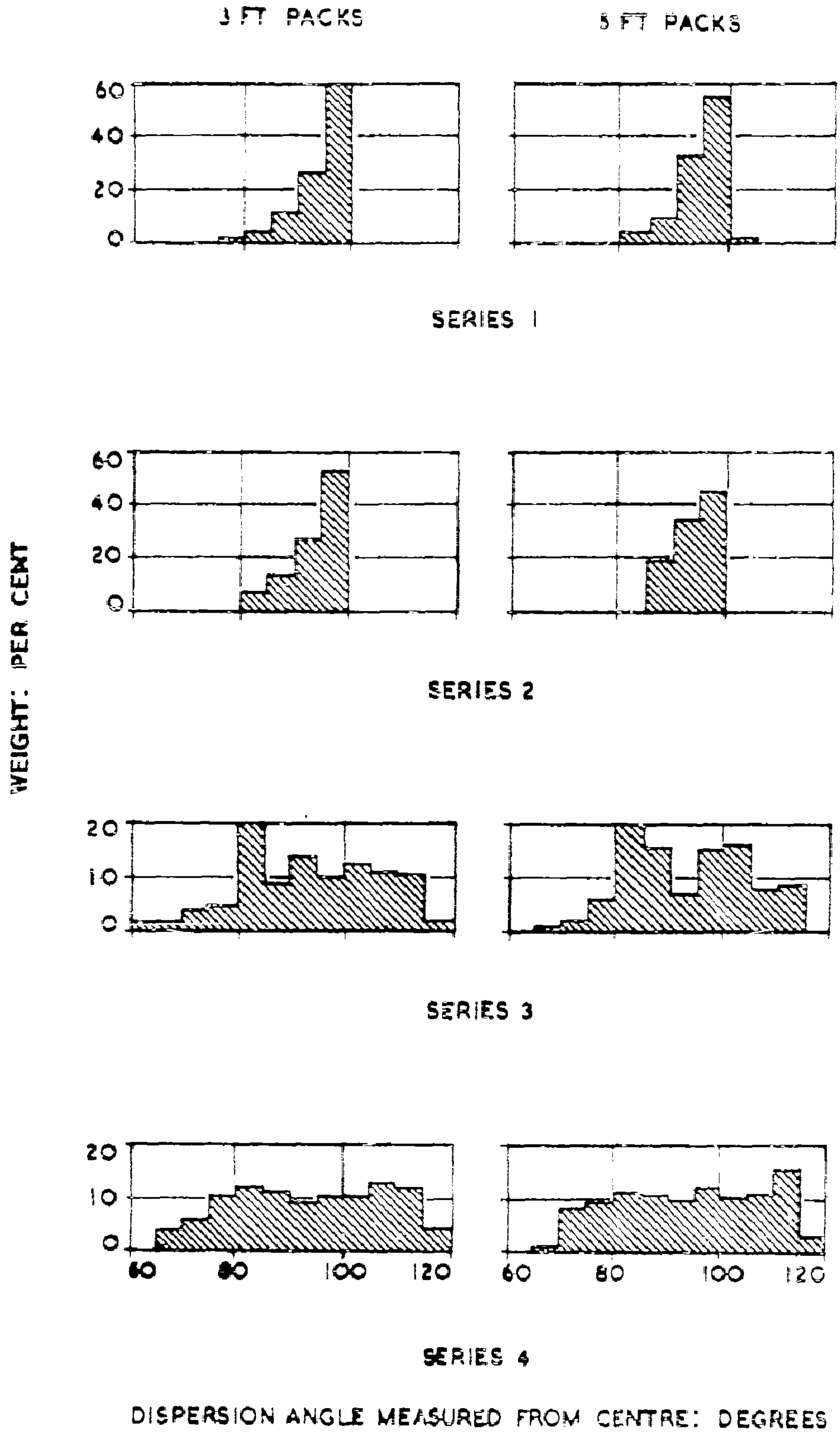
SERIES.3 — MODEL BARREL, NATURAL



SERIES.4 — MODEL BARREL, CONTROL

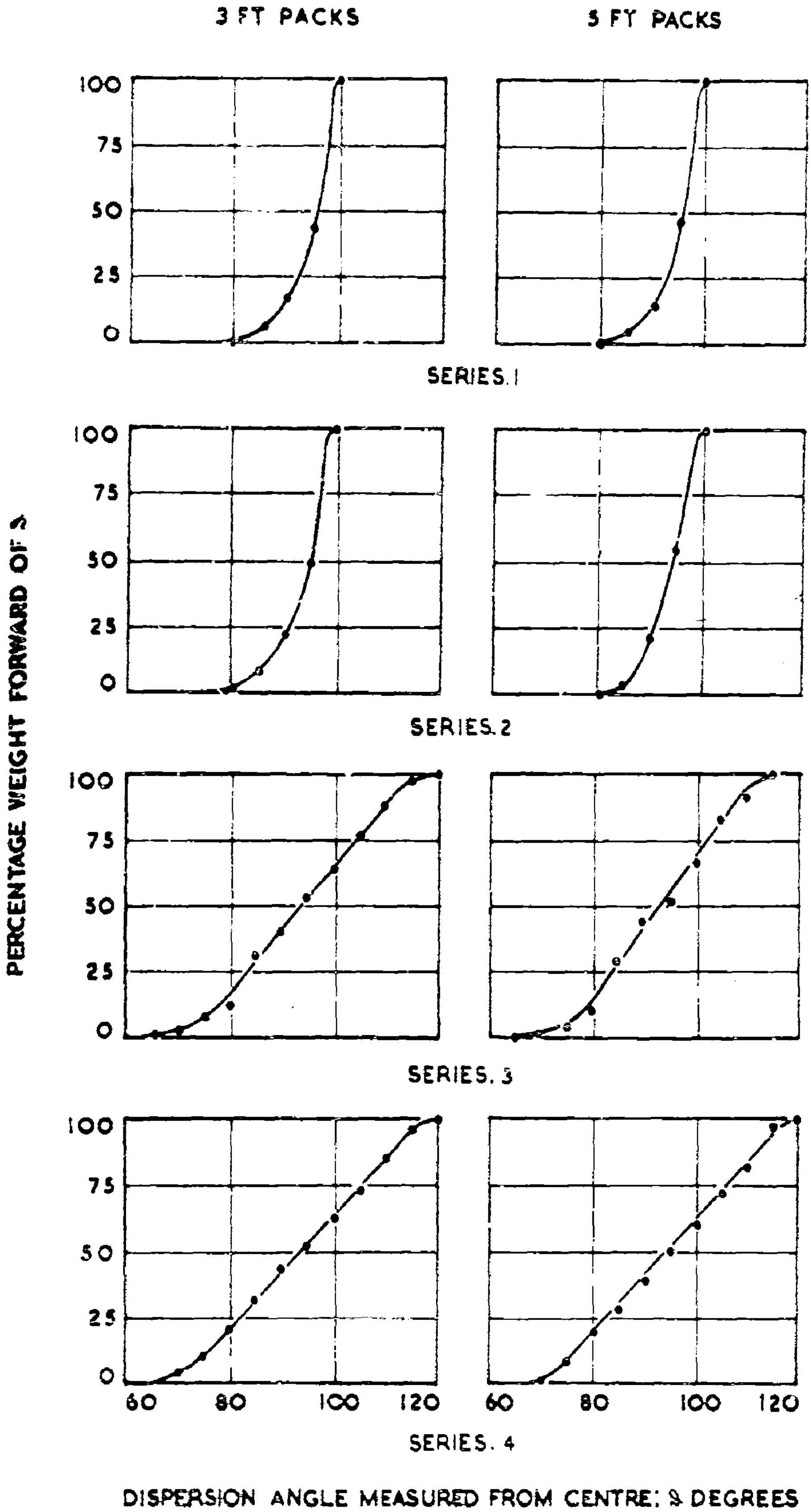
TARGET SHEETS FROM 3FT PACKS

FIG. 6



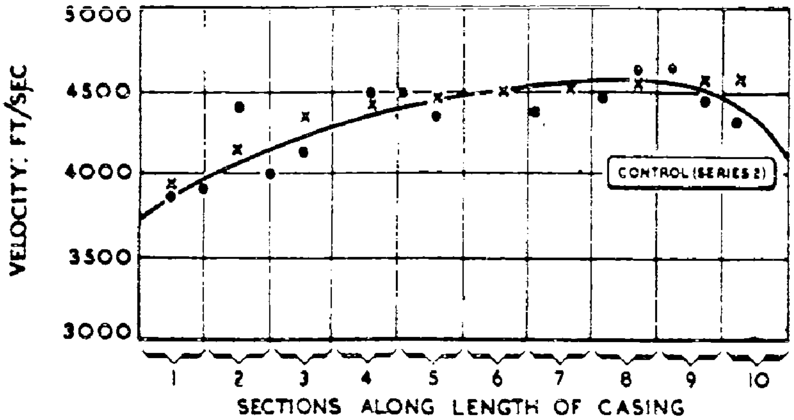
PERCENTAGE WEIGHT OF CASING FRAGMENTED INTO ANGULAR ZONES

FIG.7



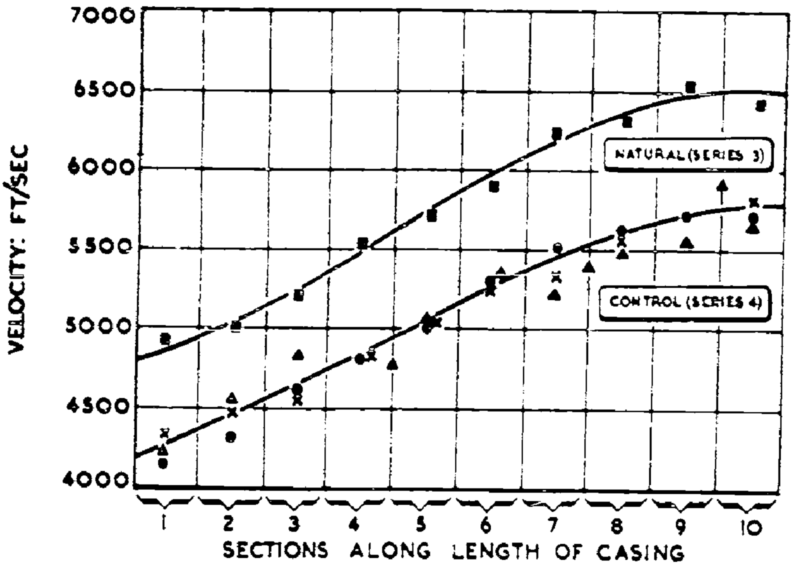
PERCENTAGE WEIGHT OF CASING
FORWARD OF ϑ

FIG. 8



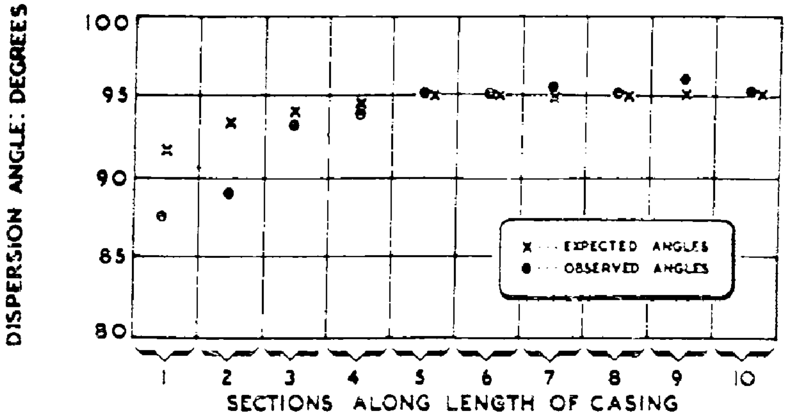
MODEL-BOMB CASING
VARIATION OF VELOCITY ALONG LENGTH

FIG. 9



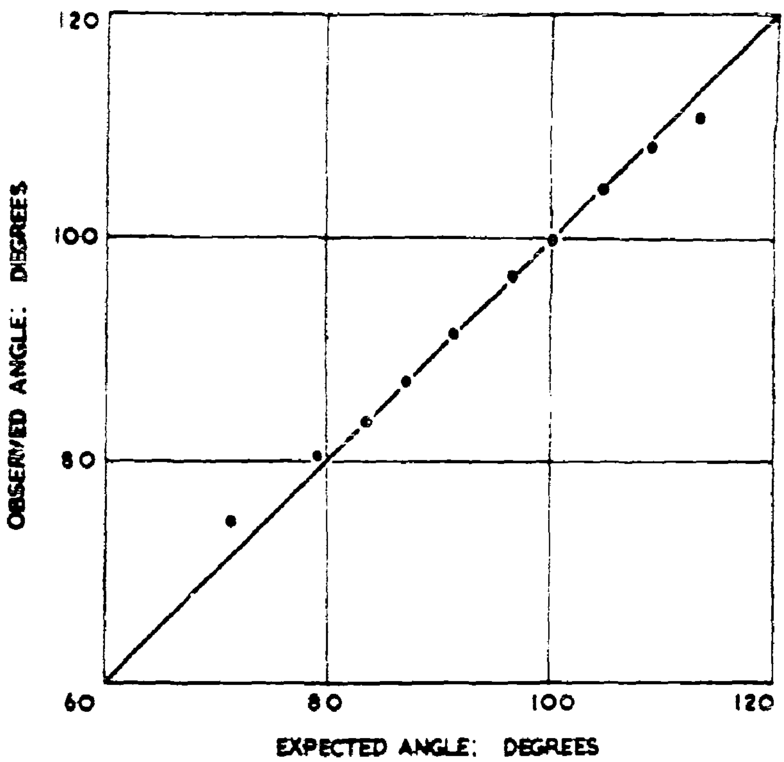
BARREL-SHAPED CASING
VARIATION OF VELOCITY ALONG LENGTH

FIG. 10



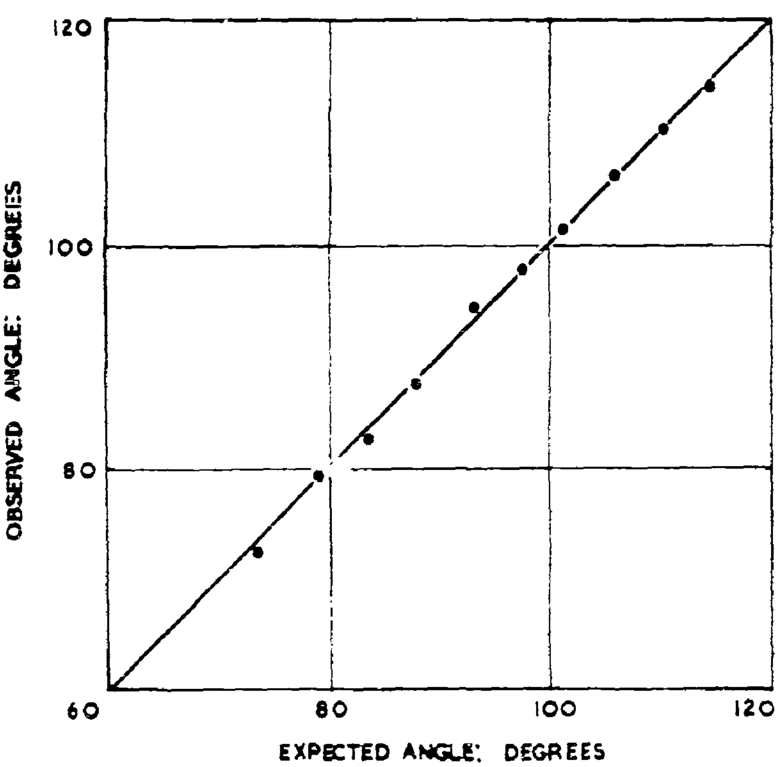
SERIES 2 COMPARISON OF EXPECTED ANGLES WITH OBSERVED ANGLES

FIG. 11



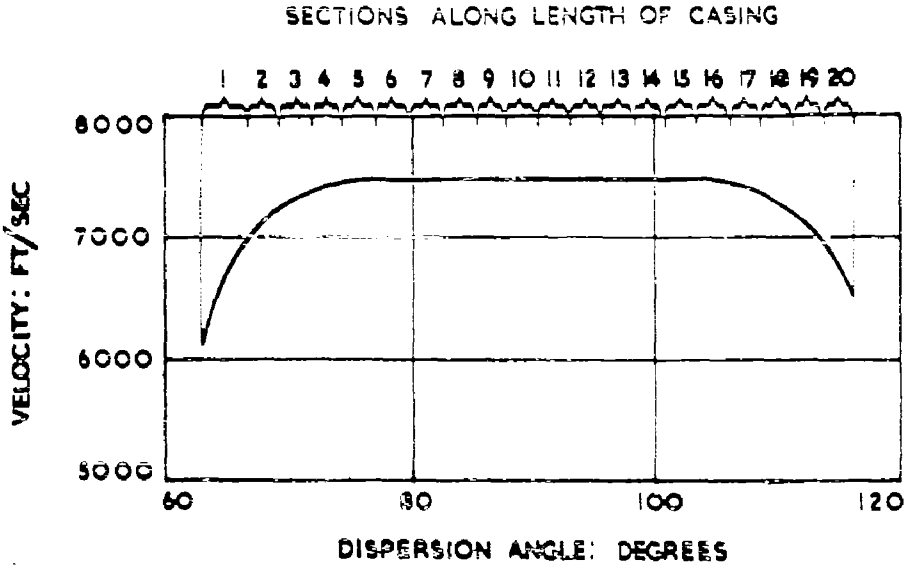
SERIES 3 COMPARISON OF EXPECTED ANGLES WITH OBSERVED ANGLES

FIG.12



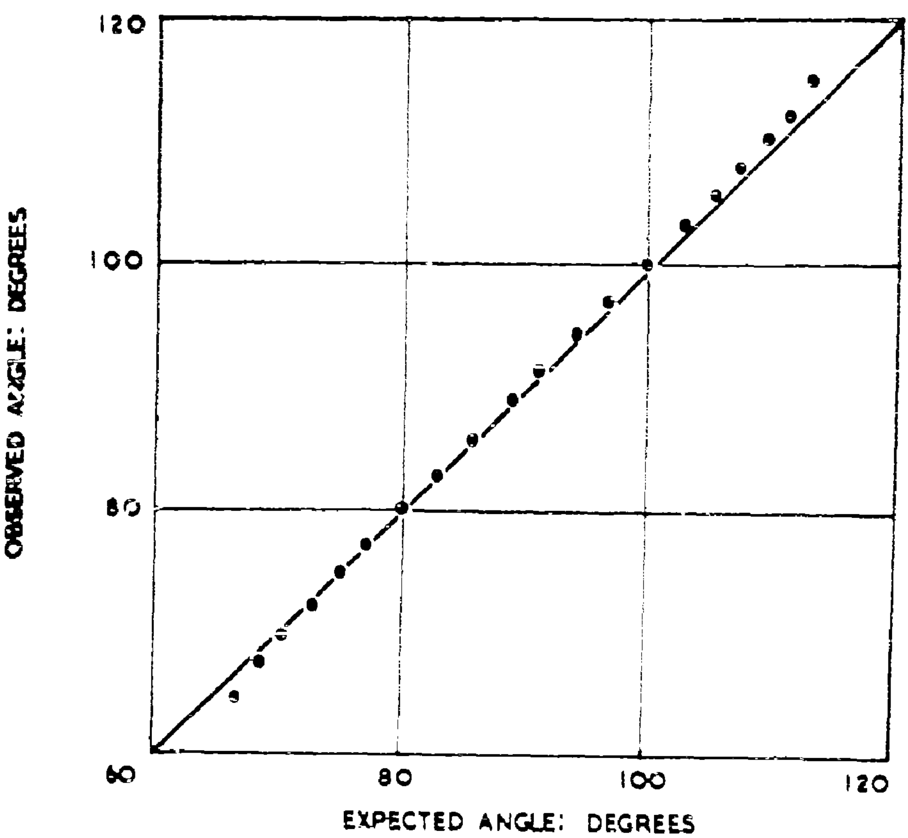
SERIES 4 COMPARISON OF EXPECTED ANGLES WITH OBSERVED ANGLES

FIG.13



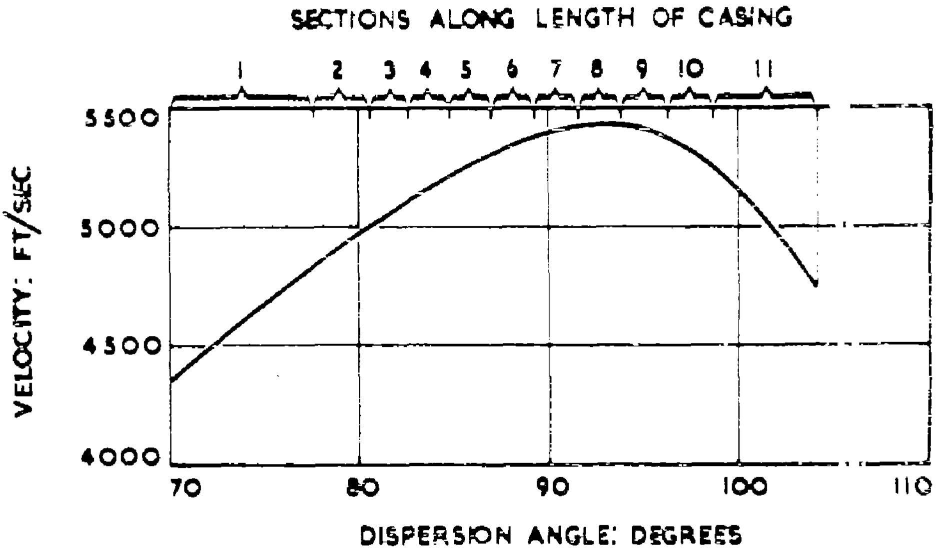
RED SHOES CASING
VARIATION OF VELOCITY ALONG LENGTH

FIG. 14



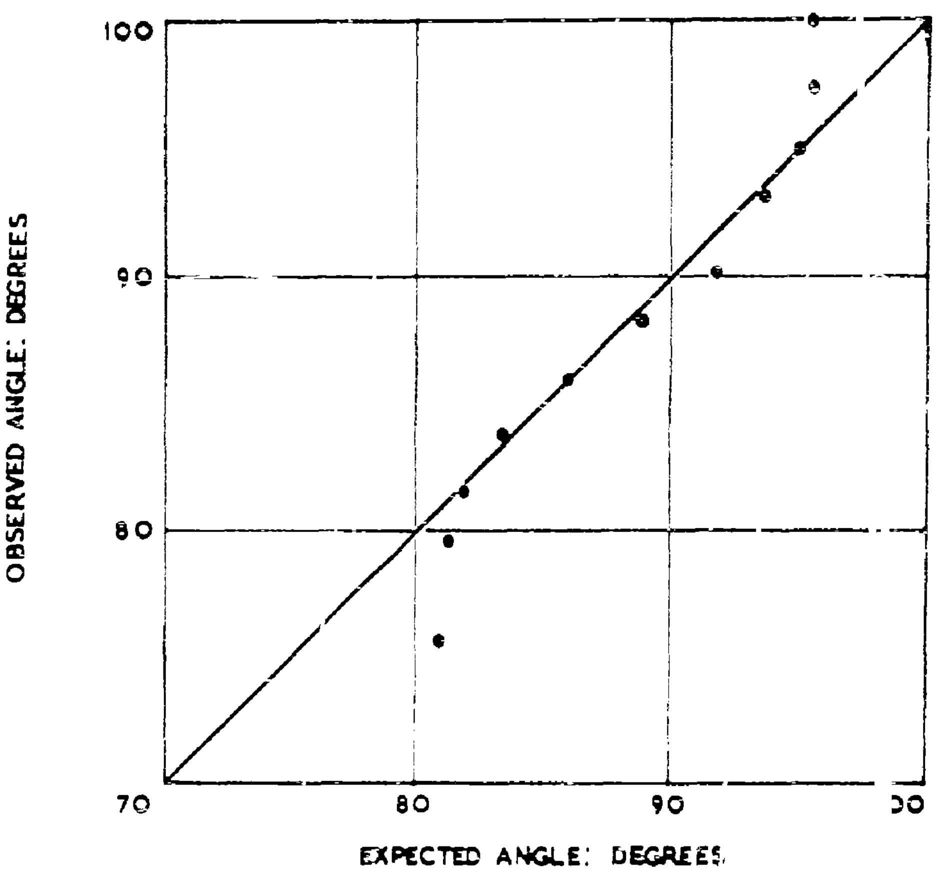
RED SHOES CASING
COMPARISON OF EXPECTED ANGLES WITH
OBSERVED ANGLES

FIG. 15



BLUE SKY CASING
VARIATION OF VELOCITY ALONG LENGTH

FIG.16



BLUE SKY CASING
COMPARISON OF EXPECTED ANGLES WITH
OBSERVED ANGLES

FIG.17

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